Predictive Equations for Energy Needs for the Critically Ill

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Nutrition may affect clinical outcomes in critically ill patients, and providing either more or fewer calories than the patient needs can adversely affect outcomes. Calorie need fluctuates substantially over the course of critical illness, and nutrition delivery is often influenced by: the risk of refeeding syndrome; a hypocaloric feeding regimen; lack of feeding access; intolerance of feeding; and feeding-delay for procedures. Lean body mass is the strongest determinant of resting energy expenditure, but age, sex, medications, and metabolic stress also influence the calorie requirement. Indirect calorimetry is the accepted standard for determining calorie requirement, but is unavailable or unaffordable in many centers. Moreover, indirect calorimetry is not infallible and care must be taken when interpreting the results. In the absence of calorimetry, clinicians use equations and clinical judgment to estimate calorie need. We reviewed 7 equations (American College of Chest Physicians, Harris-Benedict, Ireton-Jones 1992 and 1997, Penn State 1998 and 2003, Swinamer 1990) and their prediction accuracy. Understanding an equation's reference population and using the equation with similar patients are essential for the equation to perform similarly. Prediction accuracy among equations is rarely within 10% of the measured energy expenditure; however, in the absence of indirect calorimetry, a prediction equation is the best alternative. *Key words: indirect calorimetry, energy needs, prediction equations, mechanical ventilation, critical illness, nutrition support, review.* [Respir Care 2009;54(4):509–521. © 2009 Daedalus Enterprises]

Introduction

Malnutrition is associated with deterioration of lean body mass, poor wound healing, increased risk of nosocomial infection, weakened respiratory muscles, impaired immunity, organ dysfunction, and increased morbidity and mortality.[1-6] Overfeeding medically compromised patients can promote lipogenesis (transformation of excess glucose into fat), hyperglycemia, and exacerbation of respiratory failure.[7-9] Adverse consequences of overfeeding have been observed in both animal and human studies.[10] Nutrition is important to immune function, preservation of respiratory function, and mounting a stress response.

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Several studies have shown that metabolically stressed and malnourished patients have more negative outcomes and higher health-care costs. Patients with continuous energy deficits have a higher ventilator-dependence rate, longer intensive care unit (ICU) stay, and higher mortality.[11-14] Respiratory muscle strength begins to decline after a few days of suboptimal nutrition.[6] Adequate feeding significantly correlates with duration of ventilator dependence (r = 0.494, P = .03) and ICU stay (r = 0.525, P = .02). In 20 adequately fed versus 15 underfed patients, ICU stay was 39 ± 20 d and 45 ± 25 d, and ventilator duration was 54 ± 28 d and 65 ± 48 d, respectively.[15] In addition, there is a 2.1-fold higher risk of pressure ulcers in nutritionally compromised patients.[16]

Nutrition impacts outcomes in the critically ill, so accurate determination of the patient's energy requirements is vital, as underfeeding and overfeeding may have deleterious effects. This review examines the accuracy of prediction equations for caloric need, and factors that influence energy expenditure in the critically ill. Unless otherwise specified, "accuracy" is defined as a prediction within 10% of the measured energy expenditure.

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Metabolic Response

Critically ill patients undergo carefully orchestrated, complex processes to recover. Cytokines play a key role in triggering the body's adaptive responses. An elevated glucose level is the result of altered glucose metabolism from counter-regulatory hormones that blunt the responsiveness of insulin. Because this population is often malnourished and subjected to prolonged periods without nutrition, refeeding syndrome may also be more prevalent.

Cytokines

Cytokines mediate many of the nutritional and metabolic abnormalities in the critically ill. Cytokines' primary function is to maintain homeostasis. Cellular responses to cytokines protect against toxic and carcinogenic substances; however, cytokines can also cause harm, depending on the intensity and duration of their release into the circulation.

Early studies described injury response in 2 phases: ebb and flow.[17] The ebb phase typically lasts 12–48 h, and the flow phase generally lasts 7–10 d, but may continue for weeks or even months.[18,19] During the flow phase, hypermetabolism occurs, as the body attempts to heal itself while maintaining organ function.[17,20] Hyperglycemia increases proinflammatory cytokine production.[21] Excessive proinflammatory cytokine mediators, tumor necrosis factor alpha, and interleukin-1β trigger a cascade of events, such as the modulation of insulin-like growth factor 1, and glucocorticoid production. These changes may result in immunocompromise and neuroendocrine dysfunction and are associated with metabolic disturbances and increased energy expenditure.[22-26] According to Roubenoff et al, cytokines increase energy expenditure 9–10 kcal/d per ng/mL.[22] In a study by Cerra and colleagues, cytokines increased daily energy needs by 10–20%.[27] In the flow phase, even well nourished patients may develop protein-energy malnutrition within 7–10 d of ICU admission.[28] Cytokine proinflammatory inhibitors are available, but are costly, have adverse effects, and have not been shown to improve outcomes.[29]

Hyperglycemia

Prior to 2001, hyperglycemia (glucose level up to 220 mg/dL) was permissible in critically ill patients, and was attributed to normal physiologic reactions to stress. Hyperglycemia was thought to reflect the degree of stress and inflammation, especially in the early phase of injury.[29,30] Cortisol plays a vital role in the adaptation to trauma. Animal models found a 4.7-fold increase in cortisol per 100 mL, and a 1.4-fold increase in glucose, 4 hours after surgery.[31]

During stress-induced hyperglycemia, proinflammatory cytokines contribute to increasing glucose levels through gluconeogenesis (limiting the available respiratory muscle glycogen in the underfed) and glycogenolysis (indirectly increasing the counter-regulatory hormones glucagon and cortisol), and to inhibiting insulin release.[5,30,32] Effects of hyperglycemia include impaired wound healing, fluid and electrolyte imbalance, and impaired immune function. However, how to treat hyperglycemia during critical illness remains quite controversial. Limited data suggest that intensive insulin therapy (blood glucose 80–110 mg/dL) may improve outcomes in critically ill surgery patients,[30,33] but more randomized trials and a recent meta-analysis suggest that intensive insulin therapy may not provide benefit and may even be harmful.[34-36]

Refeeding Syndrome

Refeeding syndrome occurs in approximately 0.8% of hospitalized adults[37]; however, the incidence appears to be higher in critically ill ICU patients. In a 1996 study by Marik and Bedigan, 21 (34%) of 62 ICU patients developed refeeding syndrome.[38] Metabolic abnormalities from refeeding syndrome occur as a result of overzealous feeding of those with prolonged starvation, malnutrition, or substantial weight loss. When refeeding the starved, a shift in preferential fuel source occurs. Throughout starvation, insulin secretion decreases because of declining carbohydrate intake, and the preferred energy source changes from glucose to ketones and free fatty acids.[39] During that period the body may deplete its cells of phosphorus, magnesium, and potassium, but serum concentrations remain normal because of the adjustments in renal excretion rates.[40] Once nutrition intervention is initiated, carbohydrates become the primary fuel, which increases the insulin level, which drives phosphorus, magnesium, and potassium back into the cells. In addition, hyperinsulinemia has an antiuretic effect that results in sodium and fluid retention.

The hallmark sign of refeeding syndrome is hypophosphatemia, which usually occurs within 3 days of starting nutrition.[40,41] Hospital stay and ventilator dependence are significantly longer in those with hypophosphatemia.[38] Individuals at risk for refeeding syndrome include those with anorexia, alcoholism, prolonged starvation, morbid obesity with substantial weight loss, and chronic disease states that compromise nutrition status (eg, cancer, cirrhosis).[39]

Depleted phosphorus reserves translate into reduced production of myocyte adenosine triphosphate, which is needed for respiratory muscle contracture.[40] Dyspnea and diaphragmatic weakness may result from refeeding hypophosphatemia;[42] thus, respiratory dysfunction may worsen as a result of decreased diaphragm strength, and individuals may develop acute respiratory failure or failure to wean from the ventilator.[41]

Resting Energy Expenditure

Total energy expenditure includes resting energy expenditure (which is approximately 60–70% of total energy expenditure), thermic effect of food (which is approximately 8–10% of total energy expenditure), physical activity, and growth and/or disease process (including healing). Basal metabolic rate measures the minimum metabolic activity after waking and before getting out of bed. There is a small difference between basal metabolic rate and resting energy expenditure; resting energy expenditure is more commonly used and may be 75–100% of total energy expenditure in the critically ill. Normally, 60–70% of resting energy expenditure is used to maintain cell-membrane pumps, basic metabolic process, and muscular function.[17] The amount of lean body mass is the strongest determinant of resting energy expenditure, but other factors, such as age, sex, temperature, thyroid function, systemic inflammation, and disease process also influence resting energy expenditure.[17,25,26] Clinicians can evaluate whether nutritional demand is being met through the assessment of body composition, hepatic protein levels, muscle function, and respiratory function.[43,44]

Indirect Calorimetry

Indirect calorimetry remains the accepted standard for determining the energy expenditure in the critically ill, and to which the prediction equations are compared.[45] Indirect calorimetry is often underutilized due to cost (initial and ongoing maintenance), poor insurance reimbursement, and lack of trained personnel to operate the equipment and interpret the results.[7,46] In 2000, an indirect calorimeter cost $30,000 to $60,000.[17]

Indirect calorimetry measures oxygen consumption ($\dot{V}_{O_2}$) and carbon dioxide excretion ($\dot{V}_{CO_2}$) (both in mL/min), which are used to calculate the respiratory quotient (ie, the ratio of carbon dioxide excretion to oxygen consumption) and the resting energy expenditure, with the Weir equation[17,47]:

Resting energy expenditure (kcal/d)

$$= 1.44 \, (3.9 \, \dot{V}_{O_2} + 1.1 \, \dot{V}_{CO_2})$$

Respiratory quotient is used to evaluate substrate utilization. The normal physiologic range of the respiratory quotient is 0.7–1.0. A respiratory quotient > 1.0 may indicate excessive CO_2, lipogenesis, and overfeeding. A respiratory quotient < 0.7 may be due to metabolic or technical causes.[17] Caution is advised when interpreting these values, because they may be altered by stress response, underlying pulmonary disease, acid-base balance, and medications.[7,17]

Indirect calorimetry can represent the sum of resting metabolism, which includes thermogenesis, physical activity, and the catabolic effect of disease, depending on when it is measured.[48] For the thermic effect of food, 5% is commonly added if the patient was measured in the fasting state or will receive intermittent feedings; no additional calories are added for continuous feeding, because insignificant metabolic changes occur when the patient is fed nonstop throughout the day.[17,49,50] Often, an additional 5% is added in the ICU to account for activity from procedures and daily care activities, such as chest physiotherapy, repositioning, and bathing, in an otherwise sedentary population.[50,51] It may be beneficial to obtain a baseline indirect calorimetry to assess the degree of metabolic response to injury, and then follow-up with measurements to determine the transition from ebb phase to flow phase.[7] However, indirect calorimetry may not be needed in all ICU patients. If resources are limited, indirect calorimetry should be reserved for those with inadequate response to prediction equations (eg, nutritional laboratory indices such as prealbumin failure to improve), clinical signs of overfeeding or underfeeding (eg, difficulty weaning from the ventilator), and complicated energy-need determination (eg, morbidly obese).[7,52]

Indirect calorimetry may be performed intermittently or continuously.[7] Indirect calorimetry should be conducted until a steady state is achieved, which is defined by a stable acid-base balance and CO_2 production. Most studies have considered a 20–30 min indirect calorimetry an accurate reflection of 24-hour energy expenditure.[17,53]

In a study of 213 ventilator-dependents patients, approximately 25% received calories within 10% of measured energy expenditure; 32% to 93% were overfed, and 12% to 36% were underfed.[54] McClave et al argued that indirect calorimetry is warranted; compared to subjects whose energy needs were measured via indirect calorimetry, those whose energy needs were predicted from equations were twice as likely to develop a negative energy balance that was associated with longer ventilator dependence.[46] Unfortunately, metabolic monitoring with indirect calorimetry remains widely unavailable, often related to lack of resources and/or reimbursement, and clinicians must rely on prediction equations and clinical judgments[2,7,46]

Indirect calorimetry is not infallible. It may not adequately measure energy expenditure in the presence of air leak (eg, around the endotracheal-tube cuff or from chest tubes), fluctuating fraction of inspired oxygen (F_{IO_2}), F_{IO_2} > 60%, or a high pain level. In addition, factors that impact gas exchange, such as dialysis, postoperative anesthesia, and inappropriately calibrated equipment, will also lead to erroneous results.[45,46,55]

Table 1. Table 1. Prediction Equations for Resting Energy Expenditure (kcal/d)*

American College of Chest Physicians equation[27]
  25 × weight
    If BMI 16–25 kg/m² use usual body weight
    If BMI > 25 kg/m² use ideal body weight
    If BMI < 16 kg/m² use existing body weight for the first 7–10 d, then use ideal body weight
Harris-Benedict equation[59]
  Men: 66.4730 + (13.7516 × weight) + (5.0033 × height) – (6.7550 × age)
  Women: 655.0955 + (9.5634 × weight) + (1.8496 × height) – (4.6756 × age)
Ireton-Jones 1992 equation[60]
  1,925 – (10 × age) + (5 × weight) + (281 if male) + (292 if trauma present) + (851 if burns present)
Ireton-Jones 1997 equation[61]
  (5 × weight) – (11 × age) + (244 if male) + (239 if trauma present) + (840 if burns present) + 1,784
Penn State 1998 equation[56]
  (1.1 × value from Harris-Benedict equation†) + (140 × T_{max}) + (32 × $\dot{V}_E$) – 5,340
Penn State 2003 equation[56]
  (0.85 × value from Harris-Benedict equation‡) + (175 × T_{max}) + (33 × $\dot{V}_E$) – 6,433
Swinamer 1990 equation[62]
  (945 × body surface area) – (6.4 × age) + (108 × temperature) + (24.2 × respiratory rate) + (817 × V_T) – 4,349

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* Weight in kg. Height in cm. Age in years. Body surface area. in m². Maximum body temperature in the past 24 h (T_{max}) (in Celsius). Respiratory rate in breaths/min.
† Use adjusted body weight with obese patients (add 25% of excess body weight to ideal body weight).
‡ Use actual body weight.
BMI = body mass index
$\dot{V}_E$ = minute volume (in L/min)
V_T = tidal volume (in L)

Prediction Equations for Calorie Need

Typically, prediction equations are either derived from healthy human subjects during resting metabolism, with an added stress or injury factor, or from a regression equation that includes the resting metabolism of healthy subjects, adjusted for variables of illness.[56] In general, the estimates from prediction equations compare poorly to measured values; calculated values have had an error range of 7–55%.[57,58] The energy needs of the critically ill are extremely diverse, ranging from hypometabolic to hypermetabolic. In addition, confounding variables such as obesity, cachexia, edema, and multiple surgical or metabolic insults increase the difficulty of applying prediction equations.[48] We will discuss 7 prediction methods to estimate energy expenditure (Table 1) and factors that influence energy expenditure.

Table 2. Average Calories-Per-Kilogram Measured Via Indirect Calorimetry

First Author	Year	Patient Population	Calories Per Kilogram
McCarthy[48]	2000	Nonseptic critically ill	25
		Complex surgical patient	30–35
Ireton-Jones[61]	2002	Ventilator-dependent and spontaneously breathing	29 (adjusted body weight)
Cheng[63]	2002	Ventilated patients ($n = 46$)	24 ± 9
Campbell[4]	2005	Critically ill ($n = 42$)	31 ± 6
Mechanick[16]	2002	Critically ill, obese (body mass index > 30 kg/m^2)	21

American College of Chest Physicians Calories-Per-Kilogram Equation

The 1997 consensus statement of the American College of Chest Physicians indicates that calorie overload should be avoided but sufficient calories should be provided to promote anabolic function in the ICU patient. Their recommendation is 25 kcal/kg of usual body weight for most patients. With obese patients the calculation should be made with the ideal body weight (body mass index [BMI] > 25 kg/m^2).[27] If BMI is < 16 kg/m^2, because of the risk of refeeding syndrome, the calculation should be made with the patient's existing body weight, for the first 7–10 days, then the calculation should be based on ideal body weight.[27]

Several studies have compared calories-per-kilogram to measured energy expenditure (Table 2). The measured energy-expenditure range in critically ill patients is 21–35 kcal/kg. Prediction accuracy (ie, within 10% of the measured energy expenditure) with 25 kcal/kg and 35 kcal/kg was poor: 18% and 43%, respectively.[58,64]

The prediction accuracy of the weight-based equation was reevaluated because outcomes appeared to be better in a study in which 187 subjects received fewer calories. Patients who received $> 66\%$ of the calories recommended by the American College of Chest Physicians calories-per-kilogram equation (ie, 9–18 kcal/kg/d) had higher morbidity and mortality. Those researchers suggested that a therapeutic threshold may exist; exceeding the threshold may result in negative outcomes.[65]

Recently, a prospective cohort study[66] in the *Journal of the American Dietetic Association* indicated that a critically ill population ($n = 77$) with sepsis and multiple organ failure had twice the duration of stay when receiving less than 82% of their energy needs. The energy-requirement calculation was 25–35 kcal/kg, calculated with current weight of patients with normal BMI, and with adjusted body weight in those with BMI > 25 kg/m^2. The illness severity was similar among the groups. Unfortunately, that study did not account for confounding variables such as hyperglycemia and lipid infusion, both of which can result in negative outcomes.[66] Uncontrolled glucose has been associated with increased morbidity, mortality, and complications such as polyneuropathy, bloodstream infections, deep sternal wound infections, and longer ventilatory support.[33,67-70] Excessive lipid infusion may lead to hypertriglyceridemia, impaired immune function, hypoxemia, and fat-overload syndrome.[69,71] Indirect calorimetry was not used in the aforementioned study, so it is possible that energy needs were overestimated and overfeeding was the cause of the negative outcomes. However, whether excessive calories are related to negative outcomes remains controversial because of other possible confounding variables, such as that those who received $\geq 82\%$ of their estimated calorie needs were often receiving parenteral nutrition. That study does suggest that it may not be beneficial to provide 100% of caloric needs in all populations, particularly in the severely ill.

The American College of Chest Physicians calories-per-kilogram equation has poor prediction accuracy and may lead to underfeeding or overfeeding during prolonged stay. We do not support the use of this prediction method for the critically ill population.

Harris-Benedict Equations

The original Harris-Benedict equation, published in 1919, was derived from indirect calorimetry on 239 normal, healthy subjects (136 male, 103 female, 94 newborns). The equation adjusted for weight, height, age, and sex. In early investigations of energy needs, sex was identified as a determining factor in energy expenditure; healthy women used an average of 300 calories less than men.[59] Because the Harris-Benedict equation was based on a population of nonobese, healthy volunteers, to apply the Harris-Benedict equation to hospitalized patients, an additional factor is often added to account for elevated energy expenditure due to stress or injury.[2]

Although the Harris-Benedict equation accurately predicted (ie, within 14%) caloric need in the healthy population, it was unreliable when applied to malnourished and critically ill patients.[53,57,58,72] In a retrospective study of 76 ventilated medical ICU patients, the Harris-Benedict equation with a factor of 1.2 and use of actual body weight was found to be unbiased and accurate (within 15% of the measured energy expenditure), compared to a 15-min in-
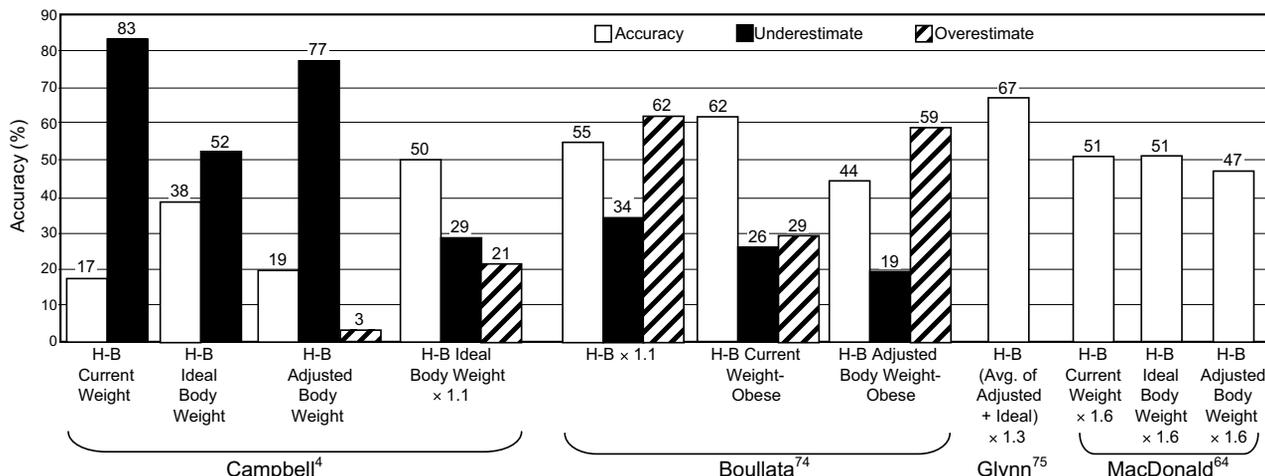
Fig. 1. Accuracy of the Harris-Benedict equation in 4 studies. "Accurate" means within 10% of the resting energy expenditure measured via indirect calorimetry.

direct calorimetry obtained a mean ± SD 8 ± 5 d after ICU admission. The Harris-Benedict equation without factors was found to be inaccurate; there was a 20% difference between measured energy expenditure and predicted energy need, and in that study accuracy was defined as ± 15% of measured energy expenditure. The Harris-Benedict equation with an added factor of 1.2, was recommended in the absence of indirect calorimetry; however, that study did not consider whether the patient was in the ebb or flow phase, and defined accuracy with a 50% greater range (15%) than have other studies (10%).[73]

Many studies have investigated the accuracy of the Harris-Benedict equation when calculated with actual versus ideal versus adjusted body weight, and with various stress factors. The studies we reviewed for this paper indicate that the accuracy range of the Harris-Benedict is 17–67%, with a strong tendency to overestimate and underestimate caloric need (Fig. 1).[4,64,72,75] Studies by Ireton-Jones and Cheng et al were consistent with previous findings that the Harris-Benedict equation tends to underestimate energy expenditure.[61,63]

In 2007 the Harris-Benedict equation was reexamined for use in the ICU adult population. The Harris-Benedict equation without added factors had a 250–900-cal/day difference from the measured energy expenditure, and with additional factors it underestimated and overestimated resting energy expenditure and was inaccurate and unreliable for ICU patients.[45] There is strong evidence not to use the Harris-Benedict equation, with or without factors, in critically ill patients.[45,76]

Ireton Jones Equations

1992 Ireton-Jones Equation. The first Ireton-Jones equation, published in 1992, was based on data from 200 patients and derived from a multivariate regression analysis that considered age, weight, sex, presence/absence of trauma, and presence/absence of burns. That studied population was predominately male, 33% were ventilator-dependent, and the age range was 15–80 y (mean age 43 y). There was no significant difference between the measured values and the Ireton-Jones-predicted values ($P > .25$ via paired t test). The validity of the equation was tested with data from another group of 100 patients with similar characteristics.[60]

The 1992 Ireton-Jones equation has had 7 validation studies; 2 found an accuracy range of 28–83% (Table 3).[56,64] It appears to have greater accuracy in young and obese patients.[56] A retrospective study with 46 mechanically ventilated ICU patients found that it overestimated energy expenditure in 12% of the subjects. Another retrospective study reported that in 37 severely underweight critically ill patients it overestimated in 43% of the patients and underestimated in another 43%.[4,63] Currently there are insufficient data to reject the 1992 Ireton-Jones equation. Many of the studies had small sample sizes. Further study is warranted.

1997 Ireton-Jones Equation. In 1997, Ireton-Jones reanalyzed the data on which the 1992 Ireton-Jones equation was based, to evaluate whether the discrepancy between the measured energy expenditure and the 1992 Ireton-Jones equation could be minimized. Statistical analysis of the 99 ventilator-dependent patients indicated that the 1992 equation could be improved; this led to the 1997 Ireton-Jones equation. The mean prediction error of the 1992 Ireton-Jones equation was −271 kcal/d (ie, it tended to overestimate energy expenditure). The 1997 Ireton-Jones equation had a mean prediction error of 8 kcal/d and provided more accurate estimates in 59% of the studied population.

Table 3. Accuracy Rates With the Ireton-Jones Equations

First Author	Year	Equation	Patient Population	Accuracy*

Frankenfield[56]	2004	Ireton-Jones1992	Mechanically, ventilated, medical, surgical, trauma	Overall ($n = 47$): 60%
				32% within 15% of measured energy expenditure
				Subdivided by weight
				   Nonobese ($n = 29$): 52%
				   Obese ($n = 18$): 72%
				Subdivided by age
				   Young ($n = 27$): 70%
				   Elderly ($n = 20$): 45%
				Subdivided by age and weight
				   Young, nonobese ($n = 15$): 60%
				   Young, obese ($n = 12$): 83%
				   Elderly, nonobese ($n = 12$): 43%
				   Elderly, obese ($n = 6$): 50%

MacDonald[64]	2003	Ireton-Jones1992	Mechanically ventilated, medical, surgical, BMI < 30 kg/m^2	Overall ($n = 76$): 28% 43% within 15% of measured energy expenditure 63% within 20% of measured energy expenditure

Frankenfield[56]	2004	Ireton-Jones1997	Mechanically ventilated, medical, surgical, trauma	Overall ($n = 47$): 36%
				40% within 15% of measured energy expenditure
				Subdivided by age
				   Young ($n = 27$): 48%
				   Elderly ($n = 20$): 15%
				Subdivided by weight
				   Nonobese ($n = 29$): 41%
				   Obese ($n = 18$): 28%
				No data for age and weight

* "Accurate" means within 10% of the measured resting energy expenditure, except where indicated.
BMI = body mass index

The 1992 Ireton-Jones equation overestimated energy need in 65% of the ventilated population, whereas the 1997 equation overestimated in 52% of those subjects. In obese patients the 1997 Ireton-Jones equation significantly correlated with the measured energy expenditure: the prediction error was only −96 kcal/d.[61] But, ironically, studies that used the 1997 Ireton-Jones equation had less accurate predictions than those that used the 1992 Ireton-Jones equation.[56] The 1997 Ireton-Jones equation was more prone to underestimation, whereas the 1992 Ireton-Jones equation was unbiased in that it underestimated and overestimated in the same percentage of patients. At least 30% of the predicted values were > 15% different than the measured values, but more accurate than the values obtained with the 1997 Ireton-Jones equation (see Table 3).[45,56,76] Thus, of the 2 Ireton-Jones equations, the 1992 version is preferred.

Penn State Equations

The original 1998 Penn State equation was derived from data from 169 ventilated critically ill trauma, surgery, and medical patients. The predicted values were compared to values from 30-min indirect calorimetry.

In 2003 the Penn State equation was modified because of research that indicated that the Mifflin St Jeor equation was more accurate than the Harris-Benedict equation in predicting resting energy expenditure, and the use of adjusted body weight for obese patients in the Harris-Benedict equation tended to underestimate caloric need. The 1998 Penn State equation used adjusted body weight for obese subjects. The 2003 Penn State equation used actual body weight. Both Penn State equations were found to be unbiased and valid by Frankenfield and colleagues, who found accuracy of 68% with the 1998 Penn State equation, and 72% with the 2003 Penn State equation. The 2003 Penn State equation successfully predicted resting energy expenditure in nonobese and obese elderly patients, and in nonobese young adults, but not in obese young adults.[56] Two other investigative teams[59,74] did not obtain such impressive results; they found accuracy of only 29–43%; however, those studies did not evaluate accuracy stratified by weight, age, or a combination of weight and age (Table 4). The 2003 Penn State equation may be useful with nonobese, critically ill patients, whereas the 1998 Penn State equation may be useful with obese, critically ill, ventilated patients. However, the limited sample sizes

Table 4. Accuracy Rates With the Penn State Equations

First Author	Year	Equation	Patient Population	Accuracy*

Frankenfield[56]	2004	Penn State 1998	Mechanically ventilated, medical, surgical, trauma	Overall ($n = 47$): 68%
				 Subdivided by weight
				  Nonobese ($n = 29$): 69%
				  Obese ($n = 18$): 67%
				 Subdivided by age
				  Young ($n = 27$): 63%
				  Elderly ($n = 20$): 75%

MacDonald[64]	2003	Penn State 1998	Mechanically ventilated medical/surgical, BMI < 30 kg/m²	Overall ($n = 76$): 29%

Frankenfield[56]	2004	Penn State 2003	Mechanically ventilated, medical/surgical/trauma	Overall ($n = 47$): 72%
				 Subdivided by weight
				  Nonobese ($n = 29$): 79%
				  Obese ($n = 18$): 61%
				 Subdivided by age
				  Young ($n = 27$): 63%
				  Elderly ($n = 20$): 85%
				 Subdivided by age and weight
				  Young, nonobese ($n = 15$): 67%
				  Young, obese ($n = 12$): 58%
				  Elderly, nonobese ($n = 14$): 93%
				  Elderly, obese ($n = 6$): 67%

MacDonald[64]	2003	Penn State 2003	Mechanically ventilated medical/surgical, BMI < 30 kg/m²	Overall ($n = 76$): 39%
Boullata[74]	2007	Penn State 2003	Ventilated in the intensive care unit	Overall ($n = 141$): 43%

* "Accurate" means within 10% of the measured resting energy expenditure.
BMI = body mass index

of and mixed results from other studies encourage further studies.

Swinamer Equation

The Swinamer equation was developed in 1990 from data from 112 mechanically ventilated, critically ill patients with trauma, surgical, and medical diagnoses. Indirect calorimetry was performed on the first or second day of admission. The Swinamer equation was derived from variables that contribute > 3% of energy expenditure, including body surface area, age, respiratory rate, tidal volume, and body temperature.[62]

Two studies ($n = 141$, and $n = 76$) that compared the Swinamer equation to indirect calorimetry found accuracy of 45% and 55%.[64,74] The accuracy was lower than that determined by Swinamer et al. The reference-population differences might explain that discrepancy. The Swinamer equation is more accurate than some; however, it is used infrequently because it is difficult to obtain all the information necessary for the equation.[64] There have been only 2 validation studies, so there are not enough data to accept or reject the Swinamer equation.[45] It may be useful in nonobese, critically ill patients, but more research is needed.[76]

Comparison of the Prediction Equations

Selecting which prediction equation to use is challenging. Understanding an equation's reference population is vital to understanding which patients the equation works with. None of the equations reviewed above predict resting energy expenditure in most ICU populations, regardless of

Table 5. Recommended Prediction Methods for the Critically Ill in the Absence of Indirect Calorimetry[64,76]

Equation	Recommendation		
	Nonobese	Obese	Ventilated, Obese
Ireton-Jones 1992*†	Yes (52% accurate)	Yes	Yes
Penn State 1998*	No	Yes	Yes
Penn State 2003	Yes (79% accurate)	No	No
Swinamer	Yes (55% accurate)	No	No
Harris-Benedict	No	No	No
American College of Chest Physicians	No	No	No
Ireton-Jones 1997	No	No	No

* Use for the general population rather than the severely critically ill.
† Not recommended for severely underweight patients.

age, race, sex, BMI or ventilator status.[74] Table 5 summarizes our suggestions on which equations to use with which patients.[64,76] More validation studies have been recommended for all the equations,[45] but with critically ill patients we do not recommend the Harris-Benedict equations, the calories-per-kilogram equation, or the Ireton-Jones 1997 equation.

The range of absolute difference among the equations is 8–15%. Equations provide a starting point for the clinician. The equations are accurate only if variables such as body temperature and minute ventilation remain unchanged.[77] Many factors influence energy expenditure, and are discussed in the following sections.

Factors That Influence Energy Expenditure and Prediction Equations

Age

Changes in metabolism and body composition, and increased risk of morbidity and mortality, are associated with aging.[56,78] Resting energy expenditure declines 1–2% per decade after the third decade of life, and declines even when body weight remains stable. An energy-prediction model based on organ and tissue mass very successfully predicted resting energy expenditure in young subjects, but overestimated it in the elderly, possibly due to the energy-expenditure decline related to loss of fat-free mass, which has a higher metabolic rate.[79] Age is a negative factor for prediction accuracy with the 1992 Ireton-Jones equation and the Harris-Benedict equation.[59,60]

Many studies are conducted in populations with a mean age of 40 y, and those results are not generalizable to the growing elderly population.[52,56] In the elderly, who have a decreased fat mass and fat-free mass, illness severity increases energy and protein requirements. Twenty kcal/kg has been suggested for predicting energy expenditure in elderly ICU patients, but that simple method is fraught with inaccuracy.[28] Of the reviewed equations, the 2003 Penn State equation has the best prediction accuracy (85%). Unfortunately, energy expenditure in the elderly remains unclear, and the available data and research are limited and often disease-specific.[78,80]

Which Weight Should Be Used in Prediction Equations?

Loss of body weight is universally associated with inadequate nutrition, and severe weight loss (> 10% of ideal body weight) suggests malnutrition. However, in the critically ill, measured weights are often skewed by edema and do not reflect true body cell mass.[27] In some patients, such as those with sepsis and trauma, volume overload may mask true weight for weeks.[19] Some argue that the use of ideal body weight is justified because lean body mass changes during the course of illness, so ideal body weight is more accurate than current body weight.[4] Also, it is usually impossible to measure fat mass and fat-free mass of a critically ill patient, so many clinicians adjust the body weight by 25%, on the assumption that 25% of fat mass is metabolically inactive. The original paper on the adjusted-body-weight equation appeared in a *Renal Dietitian Newsletter* published by the American Dietetic Association, but there has been no research that supports that equation.[81]

In non-ICU patients, use of actual weight significantly overestimates energy expenditure, and ideal body weight underestimates energy expenditure.[74] Those discrepancies led some to use adjusted body weight to account for metabolically inactive tissue, but there is little evidence to support the use of adjusted weight,[75] which significantly underestimates energy expenditure.[81]

Use of actual body weight is more accurate than use of ideal body weight or adjusted body weight in some equations.[74,82] However, a survey of nutrition-support teams revealed that clinicians disagree about which weight to use: 40% use adjusted body weight, 20% use ideal body weight, and 40% use actual weight in the equations, presumably to improve the prediction accuracy. Regardless of which weight and equation are used, there is large variability in energy expenditure, so many predicted values will differ from the measured values.[83,84] The best way to account for obesity remains to be determined.[84,85]

Obesity

Obesity, which is one of the most common chronic diseases in the United States, is growing at a disproportional rate.[86] In people 20–47 y old, obesity increased 2.2-fold between 1980 and 2004.[87] More than 50% of American adults are overweight, 32% are obese, and 5% are severely obese.[56,74] Since a large number of the population is obese, we would expect that a proportionate number will become critically ill.[85] Critically ill obese patients are at higher risk of glucose intolerance, fluid retention, ventilator dependence, hepatic steatosis, and impaired wound healing.[75,86] Controversy remains as to whether metabolically stressed obese patients can mobilize fat for oxidation, and whether critically ill obese patients should receive 100% of energy expenditure or, instead, could benefit from hypocaloric feeding.[75,88-90]

Supporters of hypocaloric feeding think it is neither necessary nor desirable to fully meet the patient's energy requirement, because adipocyte contents can be oxidized for fuel.[86,90] Hypocaloric feeding should provide 50–125 g of carbohydrate for the brain, and adequate protein to maintain lean tissue.[86] Hypocaloric feeding should improve glucose control and patient outcomes.[16,86] Opponents of hy-

pocaloric feeding argue that severely stressed patients are unable to oxidize fat.[83,86] Anecdotally, we have found a hypocaloric, high-protein diet beneficial, especially for glucose control, when initially feeding obese patients, as long as renal function is unimpaired.

Many prediction equations have been based on healthy, normal-weight subjects and tend to overestimate the energy requirement in obese patients.[75]

Most of the equations include weight, and controversy remains as to which weight to use.[89] Currently there is no one approach recommended for estimating energy expenditure in the obese, critically ill patient.[85] Use of inconsistent approaches to estimating caloric need in obese patients affects stay, mortality, and other outcomes, so standardization of technique is imperative.

Medications

Medications such as antihypertensives, anesthesia, and analgesics affect energy requirements.[91] In 20 burn patients, adrenergic blockades decreased metabolism by about 12 kcal/m²/h, and epinephrine increased energy demand up to 2.5 times the basal metabolic rate.[92] An animal study found that a combination of anesthesia and ventral midline exploratory laparotomy increased postoperative energy expenditure by 10%.[93] Another study of 10 intubated patients with severe head trauma found that high-dose barbiturate sedatives reduced energy need by up to 34%, possibly by lowering cerebral metabolism, suppressing the brain's neuronal area, and directly suppressing metabolism.[94]

Swinamer et al also found that sedatives decreased energy expenditure in 10 mechanically ventilated subjects.[95] Care of critically injured patients is multifaceted; overfeeding or underfeeding can influence outcomes.[94] Also, medication helps manage fever, which can increase the basal metabolic rate 10% for every 1°C increase above normal temperature.[91] The impact of medications should not be overlooked when determining energy needs.

Stress Factors

Use of stress factors in energy-need equations may cause considerable error, because there are no definitive guides to which situation constitutes a certain stress factor level. Stress factors range from 20% to 50% in intubated patients with sepsis. The value used is ultimately determined by the clinicians, and is very subjective and dependent on experience. Stress factors often change as medical technology advances and disease definitions change.[96] For example, in 1979, the stress-factor recommendation for sepsis was 1.8 multiplied by the estimated basal metabolic rate; 15 years later the recommendation was 1.9 multiplied by the basal metabolic rate, and the definition of sepsis had changed

from the presence of pyrexia to include multiple organ failure.[97,98] It is difficult to compare studies, because most study populations were poorly defined and did not account for advances in technology.[95]

Current Practice

According to a survey by Berger et al,[99] enteral nutrition in the surgical ICU has increased and is contributing to 75% of nutrition-support days. Obtaining intake near the predicted energy need and the measured energy expenditure is often hindered by altered gastrointestinal functioning, feeding-delay for procedures and tests, and a lack of feeding access. There tends to be a wide difference between the prescribed nutrition and the delivered nutrition, so even if indirect calorimetry is used, the next obstacle is meeting the patient's energy needs. A 2003 cross-sectional study found that after 12 days in the ICU, an average patient received only 58% of the caloric need determined by the dietitian.[2] More aggressive nutrition practices (eg, small-bowel feeding, head-of-bed elevation, and motility agents) can narrow the gap between what is needed and what is provided and tolerated. The number of patients per dietitian influences the meeting of caloric need.[2] Some argue that intentional underfeeding would benefit severely ill patients. There is controversy on whether fully meeting the caloric need is indicated, since it does not always improve outcome.[66]

Summary

Equations for predicting caloric need are inaccurate and unreliable for patients who are different from the patient population from which the equation was originally derived. The critically ill population is heterogeneous and these patients have continual metabolic change, which increases the difficulty of finding one prediction equation that will be accurate for numerous patient types. The available equations have low accuracy. Each applies only to certain types of patients, so selecting an equation is up to the clinician and is often based on past practice. Even if we determine the exact caloric requirement with indirect calorimetry, there may be a discrepancy between what is needed and what is tolerated, and it is unlikely that the patient will initially tolerate 100% of these needs.

Many of the studies have had small sample sizes and may have lacked sufficient statistical power to detect a meaningful statistical difference. Indirect calorimetry was conducted at different time points in the studies, so the subjects were probably at different points in the ebb and flow phases. In addition, different indirect calorimetry procedures and interpretations may consider different error ranges acceptable.

Many of the studies have been observational, and therefore excellent for identifying associations between factors but unable to determine cause-and-effect relationships. Observational studies cannot control confounding factors and can result in spurious associations or obscure true causal relationships. Observational studies can uncover patterns and formulate hypotheses, but randomized control trials are needed to establish causality.

Currently, no consensus exists on which of the more than 200 prediction equations should be used, and results can differ significantly among clinicians.[64] Several factors, such as clinician familiarity, ease of use, and availability of the data needed for the equation, impact equation selection and use. The equation must be used with patients similar to the reference population from which the equation was derived. Often, the elderly, the extremely malnourished, and the obese were not well represented in the reference populations. Typically, these equations only consider static variables such as age, height, weight, and sex, and do not account for metabolic changes as the body progresses through the ebb and flow phases.[46] Changes in medicine and improvements in surgical techniques may change energy needs and alter equation accuracy.[96]

Prediction equations are readily available and widely used, but must be used with caution in the critically ill, since even the most accurate equations are not accurate 100% of the time. Indirect calorimetry remains the accepted standard for determining caloric need. Overfeeding or underfeeding may be tolerated for a short period but can adversely impact outcomes in a critically ill patient in a prolonged hospital stay.

Energy needs can be accurately assessed in critically ill ventilated and nonventilated adult patients without indirect calorimetry, but prediction accuracy differs among the available equations, and is rarely within 10% of of measured energy expenditure. Currently there is no strong evidence for any of the prediction equations, so indirect calorimetry is warranted with the critically ill ventilated and nonventilated population. However, if an equation must be used, the 1998 and 2003 Penn State equations, the 1992 Ireton-Jones equation, and the Swinamer equation are worthy of consideration.

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